Role of Soil Moisture and Vegetation Feedback in Seasonal Prediction of Precipitation over the Mississippi River Basin

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Introduction

Soil moisture and vegetation are two important and closely related components of land surface conditions. Soil moisture supplies water for vegetation transpiration thus supporting vegetation growth; transpiration depletes the soil water storage, which then stresses the vegetation growth. At the same time, the soil-vegetation state is strongly coupled with the overlying atmosphere through water and energy exchanges. Precipitation and potential evaporation regulates the state of soil moisture and vegetation; the resulting condition of vegetation and soil moisture controls the actual water and energy supplies from land surface to the atmospheric boundary layer, which then impacts precipitation by modifying the atmospheric water vapor concentration and the intensity of atmospheric moist convection. These processes form a complex soil moisture-vegetation-precipitation feedback mechanism, which tends to promote the land surface memory of climate anomalies, thus causing a certain degree of climate persistence. Such land memory and the resulting climate persistence provide an important source of skill for seasonal climate predictions.

Previous studies on land-atmosphere interactions have established soil moisture feedback as an important mechanism for the persistence of regional summer drought over the US Midwest (e.g., Bosilovich & Sun, 1999; Pielke et al., 1999; Pal & Eltahir, 2001). However, the role of vegetation feedback, an important factor contributing to climate persistence elsewhere, has not been adequately considered for this region. In this project, we propose to address the impact of soil moisture and vegetation feedback on the persistence of precipitation anomalies at the seasonal time scale over the United States (focusing on Mississippi River Basin) using a coupled global land-atmosphere model. The proposed research will lead to a better understanding of the land surface memory mechanisms and their impact on seasonal precipitation prediction over the United States, and provide critical information regarding the source of precipitation predictability over this region.

Project Goals

The goals of this project are to understand the role of land surface memory in seasonal prediction of precipitation over the Mississippi River Basin, and to evaluate the contributions of vegetation feedback and soil moisture feedback to the persistence of precipitation anomalies. We propose the following hypothesis:

Soil moisture condition in the Mississippi River Basin during certain seasons significantly impacts subsequent precipitation over this region, and soil moisture-precipitation feedback can cause a seasonal persistence of precipitation anomalies;

vegetation feedback at the seasonal time scale enhances the climate persistence induced by soil moisture feedback, thus further increasing the length of land surface memory.

This hypothesis will be evaluated in this project.

Methodology

The impact of soil moisture and vegetation feedback on the seasonal precipitation prediction will be examined using a coupled global land-atmosphere model. We have identified version 2 of the Community Land Model coupled with the Community Atmosphere Model (i.e., CLM2-CAM2) as the research tool. This coupled globe model will be used at a fine resolution (1x1 degrees), and the model validation, experiments design, and results analysis will focus on the United States Mississippi River Basin. While multi-year simulations will be carried out, experiment design will emphasize implications and applications in seasonal precipitation prediction.

First, a vegetation phenology scheme will be incorporated into CLM and will be evaluated against remotely sensed vegetation data. The coupled CLM-CAM model with the new vegetation phenology scheme will then be used to perform an extensive series of experiments designed to address the following scientific issues: a) the impact of initial soil moisture conditions on subsequent precipitation over the Mississippi River Basin and its seasonal dependence; b) the vegetation feedback that enhances the impact of initial soil moisture on precipitation; c) the relative importance of soil moisture feedback and vegetation feedback in seasonal precipitation prediction over the US; d) the time scales of land surface memory associated with soil moisture, vegetation, and the combination of the two.

Results and Accomplishments

Effort during the first year (9 months, June 2003-March 2004) of this project focused on incorporating a plant phenology scheme into CLM, and evaluating the performance of the phenology scheme in the offline CLM.

The phenology scheme combines two existing schemes, one from the Integrated Biosphere Simulator (IBIS) (Foley et al., 1996) and one from White et al. (1997). The phenology model updates the change of LAI at the daily time scale, through scaling the maximum LAI (LAI_{max}):

, *where* D is the predicted phenology factor, [0, 1]. LAI_{max} here refers to the maximum LAI that each plant functional type (PFT) can possibly obtain during the course of one year at a specific location, and is prescribed based on the MODIS LAI data and the University of Maryland land cover classification data; D depends on the hydrometeorological conditions, and is predicted by the scheme.

The phenology scheme considers two types of deciduousness: winter deciduousness that is controlled by temperature and drought deciduousness controlled by water availability. For some plants (especially grasses), both the impacts of temperature and water limitation are considered. Factors considered for the temperature-controlled phenology include temperature threshold, growing degree day requirement, and photoperiod requirement; for water-controlled phenology, soil water potential provides the main predictor. Leaf display of woody plants and shrubs are predicted by either the winter deciduous phenology scheme or drought deciduous phenology scheme according to their plant types. Grass deciduousness depends on the multiplicative effects of the winter deciduousness and the drought deciduousness. This is justified by observations indicating that water stressed plants are more vulnerable to freezing damage.

The winter deciduous phenology scheme predicts leaf green-up, development and senescence, using 10-day average air temperature (T10) and accumulated growing degree days (AGDD). The base temperatures for AGDD are 0 ºC for trees and -5 ºC for grasses. The followings are the winter phenology for trees and grasses, respectively:

if T_{10} < max (0 ºC, coldest monthly temperature)

otherwise.

if $T_{10} < 0$ °C
otherwise.

For the leaf offset of deciduous broadleaf plant types, a photoperiod requirement is considered as follows:

if [$L_d \leq 660$ min. and $T_{soil} < 11.5$ °C] or $T_{soil} < 2.0$ °C
otherwise.

where L_d is the length of day time (photoperiod) in minute and T_{soil} is the daily soil temperature. Comparison with MODIS LAI data indicates that in North America, accounting for the impact of photoperiod corrected a severe model bias (late by up to two months) in the leaf senescence date.

The drought deciduous phenology scheme predicts leaf shedding based on 10-day running mean of plant water stress factor (*WLT*). This factor limits photosynthesis and transpiration, ranging from 0 at the permanent wilting point to 1 at saturation. The leaf shedding is estimated by the following,

where f_{root} is the fraction of the root biomass within soil layer j, and _ is the soil potential.

For the Mississippi River Basin, a considerable fraction of vegetation cover is crop. In our phenology scheme, crops during their growing season are treated similar to grasses, with their leaf onset/offset dates prescribed to reflect the anthropogenic control on plantation and harvesting. This allows crops to respond to cold stress and water stress between the plantation and harvesting time. The plantation and harvesting dates were estimated based on the MODIS NDVI data; the rooting depth has been modified to reflect the differences between different types of crops (mainly wheat vs. maize).

The performance of the phenology scheme over North America was examined in detail. Validation against the MODIS LAI data demonstrated a very good agreement between model prediction and satellite observations in canopy seasonal variations (see Figures 1 and 2). This work is documented in a manuscript that Yeonjoo Kim is preparing. The MODIS/Terra LAI data for different plant functional types used for model validation are adopted from Tian et al. (2004).

In addition to works on the phenology scheme, model development during the 1st year of the project also yields an improved canopy hydrology scheme. In CLM, representation of canopy hydrological processes did not consider the impact of rainfall sub-grid variability. As a result, the interception loss of precipitation was overestimated by a factor of two or even more, causing mischaracterization of the water and energy flux exchanges between land surface and atmosphere. To address this model deficit, the canopy interception scheme of Eltahir & Bras (1993) and Wang & Eltahir (2000) enhanced by remotely sensed rain rate data (Grecu & Anagnostou, 2001,02) has been incorporated into CLM. The impact of this model improvement is documented in a manuscript that Dagang Wang is preparing. It is expected that including this interception scheme in the coupled CLM-CAM model will lead to a more realistic estimate of water partitioning among storages of different residence times at the land surface. The partitioning of water among reservoirs of different residence time at the land surface significantly impacts the land surface memory through soil moisture and vegetation feedbacks in the coupled model.

Future Work

Our work in the next two years will focus on improving our understanding of the contribution of soil moisture feedback and vegetation feedback to the seasonal prediction of precipitation in the Mississippi River Basin. This will be done through numerical experiments using the coupled CLM-CAM model. We will start with investigating the impact of initial soil moisture conditions on precipitation through soil moisture feedback, and expect to complete this part in the second year of the project; during the third year of the project, we will focus on how vegetation feedback modifies the strength of soil moisture-precipitation feedback over vegetated land.

Publications from this project

Our research in the first year of this project is documented by two manuscripts that are currently under preparation. We expect to submit them to peer-reviewed scientific journals by the end of the summer 2004:

Kim Y, Wang GL (2004) Simulating the vegetation phenology in North America: results from CLM. Manuscript in preparation

Wang DG, Wang GL, Anagnostou EN (2004) Incorporating rainfall observation into models to improve land-atmosphere interactions modeling. Manuscript in preparation

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Figure 1: LAI in North America from January to December predicted by our phenology model.

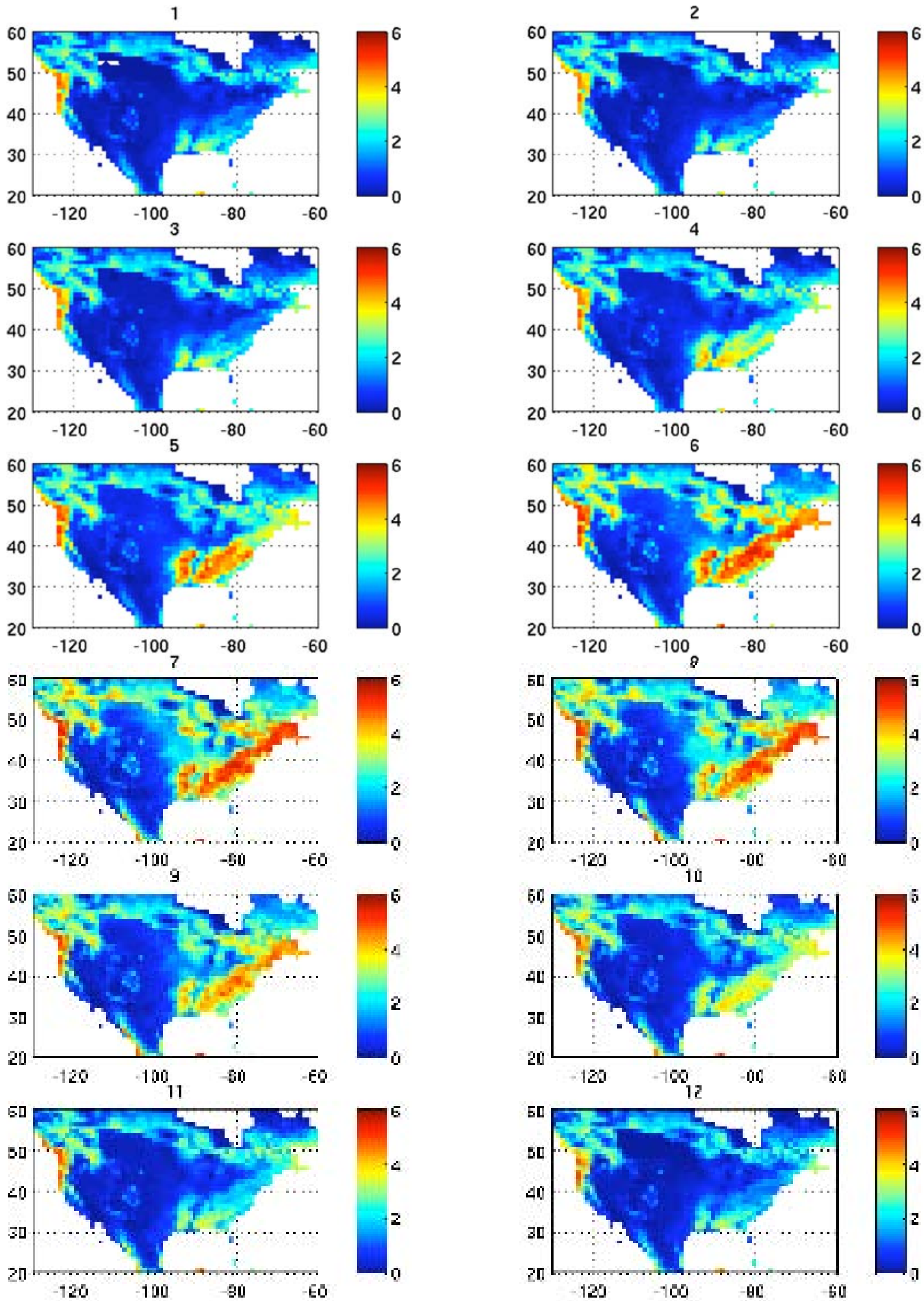

Figure 2: Observed LAI in North America from January to December, based on the MODIS LAI data (Tian et al., 2003).

Work plan for coming year

Planned research for the coming year focuses on the response of precipitation simulated by the coupled model to initial soil moisture conditions in the Mississippi river basin in the absence of vegetation feedback and how such response varies with season. Another focus is to quantify the time scale of land memory carried by soil moisture-precipitation feedback.

Due to the lack of data for soil moisture, a model-based estimate of soil moisture climatology will be first established and will be used as the control state of soil moisture for subsequent experiments. We will first run the coupled model for twelve years, with the newly added leaf phenology scheme predicting LAI seasonal variations. The soil moisture simulation during the last ten years will then be analyzed to produce a model-based daily soil moisture climatology. We expect to complete this part by the end of summer 2004.

Four groups of simulations, each including a control and several sensitivity experiments, are planned, with each group starting from the first day of a different season (e.g., January 1, April 1, July 1, and October 1). Depending on the experiment results, similar exercises will then be added for each month of certain season(s). The model-generated climatological soil moisture at the corresponding time of the year will be used to initialize the model in control simulations; experiments with different initial soil moisture conditions (i.e., wetter or drier than the control) will be performed to document the sensitivity of future precipitation to initial soil moisture anomalies. Here the wet and dry initial conditions are defined as a percentage increase or decrease of soil water content with respect to the control. In the sensitivity experiments, the initial soil moisture anomalies will be imposed across the North America or a fraction of it centering around the Mississippi River Basin; soil moisture initialization elsewhere will be the same as in the control. Vegetation seasonal variations will be predicted by the phenology scheme in control simulations; the model-generated LAI resulting from the control will then be used to prescribe LAIs for the corresponding sensitivity experiments in order to eliminate the impact of vegetation feedback and focus exclusively on the impact of soil moisture-precipitation feedback.

For all the control and sensitivity experiments, an integration of several months up to one year is planned, with the actual length of model integration depending on the time scale of climate persistence. Specifically speaking, in the event that significant, consistent difference between control and a sensitivity experiment lasts through a planned simulation period, additional model integration time will be added. We expect to start preparing for another manuscript by March 2005 documenting the contribution of soil moisture feedback to the land memory of precipitation anomalies and the quantification of the time scale related to such memory.